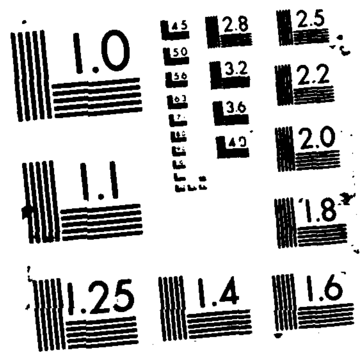
AD-A185 674 COMPLETELY MAGNETICALLY CONTAINED ELECTROTHERMAL THRUSTERS(U) SEITEC INC CLEVELAND OH G R SEIKEL ET AL. 05 JUL 87 SEITEC-8715 AFOSR-TR-87-1164 F49620-84-C-0114 1/1

UNCLASSIFIED F/G 21/3 NL


1.0
1.1
1.25
1.4
1.6
1.8
2.0
2.2
2.5
2.8
3.2
3.6
4.0

Unclassified

SECURITY CLASSIFICATI

AD-A185 674

DTIC FILE COPY 2

DTIC ELECTE OCT 0 1 1987 S D

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION: Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; distribution is unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S): SeiTec Report 8715	5. MONITORING ORGANIZATION REPORT NUMBER(S): AFOSR-TR- 87-1164
6a. NAME OF PERFORMING ORGANIZATION: SeiTec, Inc. / 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION: AFOSR/NA
6c. ADDRESS (City, State and ZIP Code): P.O. Box 81264, Cleveland, OH 44181	7b. ADDRESS (City, State and ZIP Code): Building 410, Bolling AFB DC 20332-6448
8a. NAME OF FUNDING/SPONSORING ORGANIZATION: AFOSR/NA / 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: ~~Contract~~ F49620-84-C-0114
8c. ADDRESS (City, State and ZIP Code): Building 410, Bolling AFB DC 20332-6448	10. SOURCE OF FUNDING NOS.

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.
65502F	3005	A1	

11. TITLE (Include Security Classification) (U) Completely Magnetically Contained Electrothermal Thrusters

12. PERSONAL AUTHOR(S) Seikel, George R. and Franks, Clifford V.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Yr., Mo., Day)	15. PAGE COUNT
Final Technical	FROM 84 Sep TO 85 Aug	1987 Jul 5	49

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB. GR.	Electric propulsion; Plasma, Electrothermal, and MPD thrusters

19. ABSTRACT (Continue on reverse if necessary and identify by block number) Conceptual designs of potentially attractive high performance thrusters are defined. These are a kW steady-state radiation-cooled DC thruster and a MW quasi-steady DC thruster. These thrusters offer the potential for long operating life with low erosion rates and 50 to 100% improvements in performance over prior plasma thrusters. The kW thruster would be a prototype of a radiation-cooled electric thruster for future electric propulsion missions. The MW thruster would be an inexpensive experiment to define the potential of subsequent very-high power, steady-state thrusters which would utilize superconducting magnets. The kW thruster would use xenon propellant and the MW thruster would use argon propellant. Both should operate at efficiencies of 50 to 80% in the 2500 to 3000 second specific impulse range.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS ☐	21. ABSTRACT SECURITY CLASSIFICATION: Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE NUMBER (Include Area Code)	22c. OFFICE SYMBOL
Julian M Tishkoff	(202)767-0465	AFOSR/NA

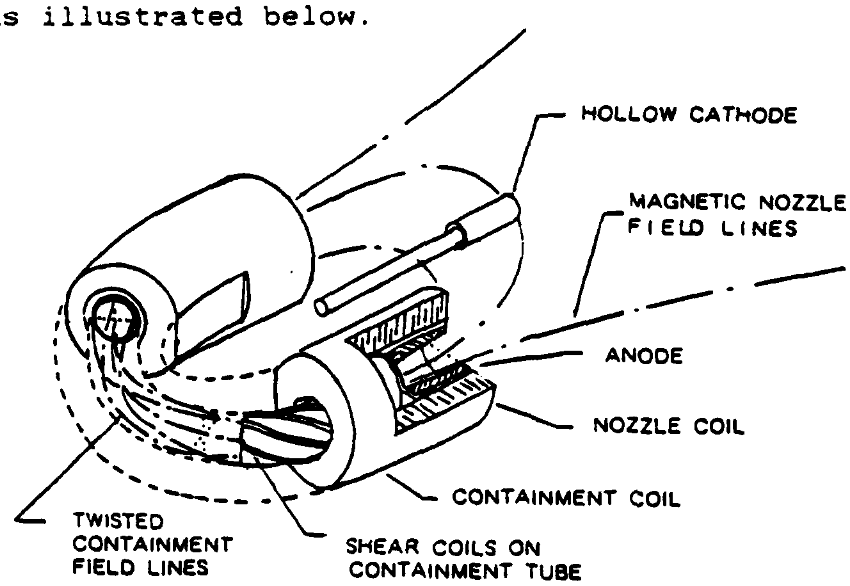
87 9 24 080

AFOSR-TR- 87-1164

Executive Summary

Technical Results

Potential Air Force orbit raising and station keeping missions could be attractively performed with electric propulsion if high efficiency plasma thrusters could be developed in the specific impulse range of 2000 to 3000 seconds. SeiTec, Inc. has developed a concept for completely magnetically contained electrothermal thrusters which offers the potential of obtaining an efficiency between 60 and 80 percent in the specific impulse range of 2000 to 3000 seconds. The basic concept of these thrusters is that thrust is produced by the expansion of a hot plasma in a pair of magnetic nozzles, as illustrated below.



NOTE: MOST FIELD COILS AND STABILIZING WINDINGS OMITTED TO SHOW DETAIL

DC Completely Magnetically Contained Thruster Concept

Upstream containment of the plasma between the nozzles in these thrusters is achieved by a magnetic containment system. This system exploits existing stellarator technology to provide stable plasma containment. This concept uses six shear coil windings in which adjacent windings carry equal and opposite current. These windings produce both a twist in the magnetic containment field lines which increases with the value of the minor radius (i.e. has "shear") and also cause a line of minimum magnetic energy to be created in the center plane of the torus at a fraction of the containment tube's radius inside the containment tube's rear wall. This magnetic field system should provide stable containment for plasmas with pressures up to a few percent of the energy density of the magnetic flux density (B); i.e. its magnetic pressure, $B^2/2\mu_0$ (where μ_0 is the permeability of free space).

In this thruster concept, the propellent is introduced into the thruster thru the wall of the thruster's nozzles, the anodes of a DC thruster. The plasma can conceptually be heated by any method: DC, RF, microwaves, or even by injection of anti-matter. The simplest, lightest, and cheapest method of plasma heating is, however, by a DC discharge; therefore, effort on this contract was concentrated on this approach. For the proposed DC thruster, plasma heating is accomplished by a discharge between the anodes located inside the magnetic nozzle coils and a downstream hollow or filament cathode which is located on a magnetic field line that passes near the center lines of the anodes.

This completely magnetically contained thruster concept directly builds on the best of the past magnetoplasmadynamic (MPD) thruster technology: the applied-field thrusters. Since this thruster concept eliminates the physical upstream insulator of prior thrusters it avoids the inefficiencies, operating limits, and life limits associated with backplate wear and erosion in prior thrusters. In addition, this novel concept permits the shape of magnetic nozzles to be optimized to maximize the efficiency of the expansion process.

The objective of this contractral effort was "to develop a conceptual design of a stable totally magnetically contained high performance 'U' shaped electrothermal thruster". Heating was to be accomplished either by a cross-field discharge generated by a single downstream cathode or by induction heating. In addition, estimates were to be made of the potential performance improvements that this thruster would offer over alternative electric thrusters.

Conceptual designs of both a kilowatt steady-state thruster and a megawatt quasi-steady thruster are defined in this report. Analysis herein indicates both have the potential of approaching efficiencies of 80%, at a discharge voltage of 400 to 600 volts. Such an efficiency would be far higher than that available from any alternative electric propulsion system in the 2000 to 3000 second specific impulse range.

Similar analysis of the prior NASA high efficiency (37% at 2200 seconds) downstream cathode MPD thruster indicates that its performance was both directly and indirectly limited by backplate losses. Directly due to the losses, and indirectly due to the use of a very rapidly expanding magnetic nozzle field to reduce direct backplate losses, but which is not optimum for the desired expansion process.

The kilowatt thruster conceptual design developed under this contract could lead directly to an attractive low power propulsion system. It uses xenon propellant, a downstream hollow cathode which requires only a few percent of the propellant flow, and a nominal 0.03 Tesla containment field. It would operate in a regime in which the DC discharge would primarily heat the plasma electrons. As the hot-electron cold-ion plasma expands in the magnetic nozzles of the thruster, the random energy of the electrons will be converted to directed ion energy. This is accomplished by an electric field which the plasma induces in order to maintain its charge neutrality. If the magnetic nozzles are properly shaped, thermal conduction in the electron gas will significantly improve the performance over that which would be obtained witn an adiabatic expansion.

The megawatt quasi-steady thruster conceptual design developed under this contract is envisioned to be a relatively inexpensive experiment to determine the potential of very-high power thrusters of this type. An eventual very-high power propulsion system would be envisioned to also operate with similar DC power but would require a high-strength superconducting magnet system, for steady state operation.

This quasi-steady thruster design uses argon propellant, a downstream hot tungsten filament cathode, and a nominal 1.0 tesla magnetic containment field. It would operate in a regime in which the DC discharge would primarily heat the plasma ions. The resulting hot-ion cool-electron plasma expansion in the magnetic nozzles of the thruster would be essentially adiabatic.

Both of these thruster designs have the same physical size. The 33 times higher strength containment field of the MW thruster, however, gives it over a thousand times higher magnetic pressure; therefore, it can operate at a thousand times higher plasma pressure and power, if a steady-state design can be defined to handle the thermal heat rejection of losses.

It is recommended that contractual effort be initiated to define an engineering design to the level required for subsequent fabrication and proof-of-concept testing of at least both the kW thruster and the hardware required to test it.

Team

All technical effort under this contract was performed by George R. Seikel, the Principal Investigator (PI) and President, SeiTec, Inc. and Clifford V. Franks, Senior Engineer, SeiTec, Inc. who, also, gratefully acknowledge the assistance and suggestions regarding this work provided by Dr. Leonard H. Caveny, Program Manager for this contract.

Presentations and Publications

At Dr. Caveny's request the contract PI did present a review of the preliminary results obtained under this contract at the 1985 AFOSR/AFRPL Rocket Propulsion Research Meeting, 19-21 March, 1985 at Lancaster, CA; a summary of the presentation with figures is included in the meeting proceedings. Also at Dr. Caveny's request a paper containing the results of the body of this report was summitted, accepted, and presented at the AIAA/DGLR/JSASS 18th International Electric Propulsion Conference, September 30 - October 2, 1985, at Alexandria, Va. This paper was published by the American Institute of Aeronautics and Astronautics (AIAA) as: Seikel, G. R. and Franks, C. V.: "Completely Magnetically Contained Electrothermal Thrusters." AIAA 85-2053, 1985. No other presentations or publications of these results have been made.

Table of Contents

List of Tables

Page

List of Figures

List of Figures (continued)

COMPLETELY MAGNETICALLY CONTAINED ELECTROTHERMAL THRUSTERS

Summary

Conceptual designs of potentially attractive high performance thrusters are defined. These are a kW steady-state radiation-cooled DC thruster and a MW quasi-steady DC thruster. These thrusters offer the potential for long operating life with low erosion rates and 50 to 100% improvements in performance over prior plasma thrusters. The kW thruster would be a prototype of a radiation-cooled electric thruster for future electric propulsion missions. The MW thruster would be an inexpensive experiment to define the potential of subsequent very-high power, steady-state thrusters which would utilize superconducting magnets. The kW thruster would use xenon propellant and the MW thruster would use argon propellant. Both should operate at efficiencies of 50 to 80% in the 2500 to 3000 second specific impulse range.

I. Introduction

The basic concept of the magnetically-contained electrothermal thruster is that thrust is produced by the expansion of hot plasma in a pair of magnetic nozzles, as illustrated in Fig. 1. The plasma can conceptually be heated by DC, RF, or microwave power. Since only DC heating appears to be practical for an on-board power source because of power conditioning requirements, it is the only heating approach considered herein. For DC heated thrusters, thrust-producing mechanisms other than electrothermal are simultaneously present, but for the thrusters defined in this study the electrothermal mechanism should be dominant.

This completely magnetically contained thruster concept directly builds on the best of the past magnetoplasmadynamic (MPD) thruster technology: the applied-field thrusters. It exploits existing stellarator technology to provide stable plasma containment, and by eliminating the upstream thruster insulator avoids the inefficiencies, operating limits, and lifetime limits associated with the physical backplate of the prior thrusters. By using magnetic containment of the plasma, it avoids the specific impulse limitations of conventional heat transfer limited electrothermal thrusters.

Previous applied-field MPD thruster experiments demonstrated significant advantages for these thrusters over the self-field MPD thrusters, as reviewed by Seikel et al, Ref. 1. The addition

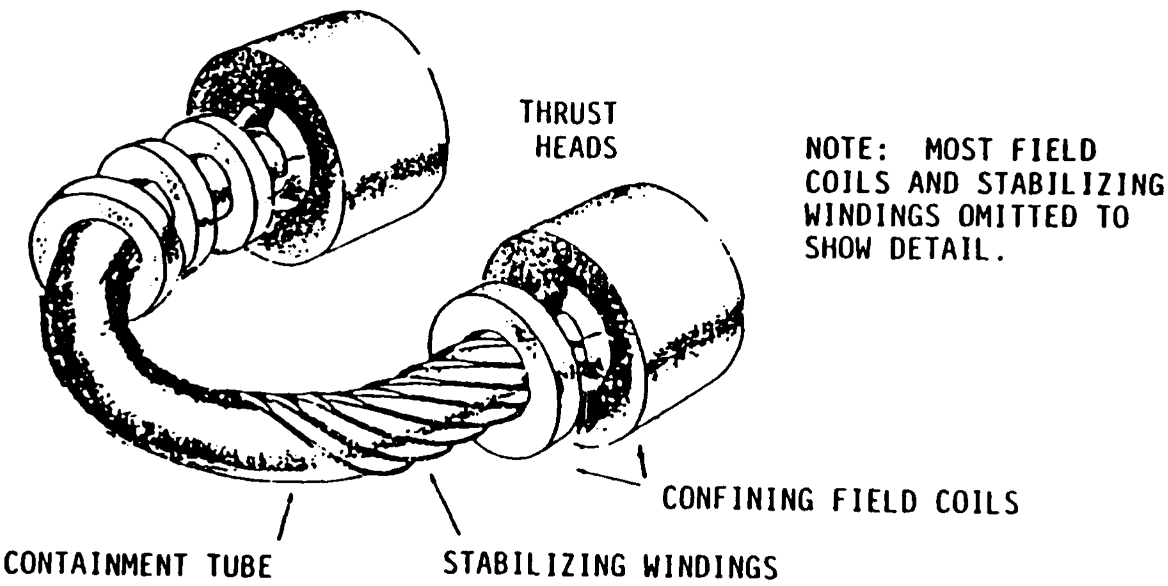


Fig. 1 - Magnetically Contained Electrothermal
MPD Thruster Concept

of an applied-field to the thruster increases the discharge operating voltage. This both increases the efficiency potential of the thruster, and, by lowering current at constant power, reduces electrode wear. Also, all plasma thrusters deposit a significant fraction of their discharge energy in heating; the applied-field provides a magnetic nozzle for these thrusters which results in a better conversion of the plasma heating to thrust. In addition, the thrust density of the applied-field thrusters is limited only by the applied magnetic field strength which can be independently selected, whereas the thrust density of the self-field thrusters is limited by their self-field. Since their self-field is a function of only the discharged current, reasonable performance can only be obtained at very high currents and power.

II. Prior Results for MPD Thrusters with Applied-Magnetic Fields

Only the most significant of these prior MPD thruster results are discussed. A more detailed review is contained in Seikel, et al, Ref. 1. Fig. 2 illustrates a pulsed megawatt MPD thruster which used a superconducting magnet to provide a high strength applied magnetic field. As indicated in the thrust and power as a function of magnetic field strength, the voltage and, therefore, also the power at the constant current of 8kA is increasing linearly with the magnetic field strength. The thrust is, however, increasing greater than linearly with applied magnetic field. Therefore, the efficiency which is proportional to the thrust squared divided by the power is also increasing with magnetic field strengths for magnetic field strengths greater than 1 Tesla. Unfortunately, in these experiments a direct determination of thruster efficiency was not possible; this was due to the pulse nature of the experiment which did not permit accurate assessment of the mass per shot. In later quasi-steady experiments, for which mass flow could have been more accurately obtained, thrust measurements were not made.

Fig. 3 illustrates a 25kW radiation cooled MPD thruster which made use of the same superconducting magnet as the prior megawatt pulsed thruster. Performance of this thruster, with argon propel-

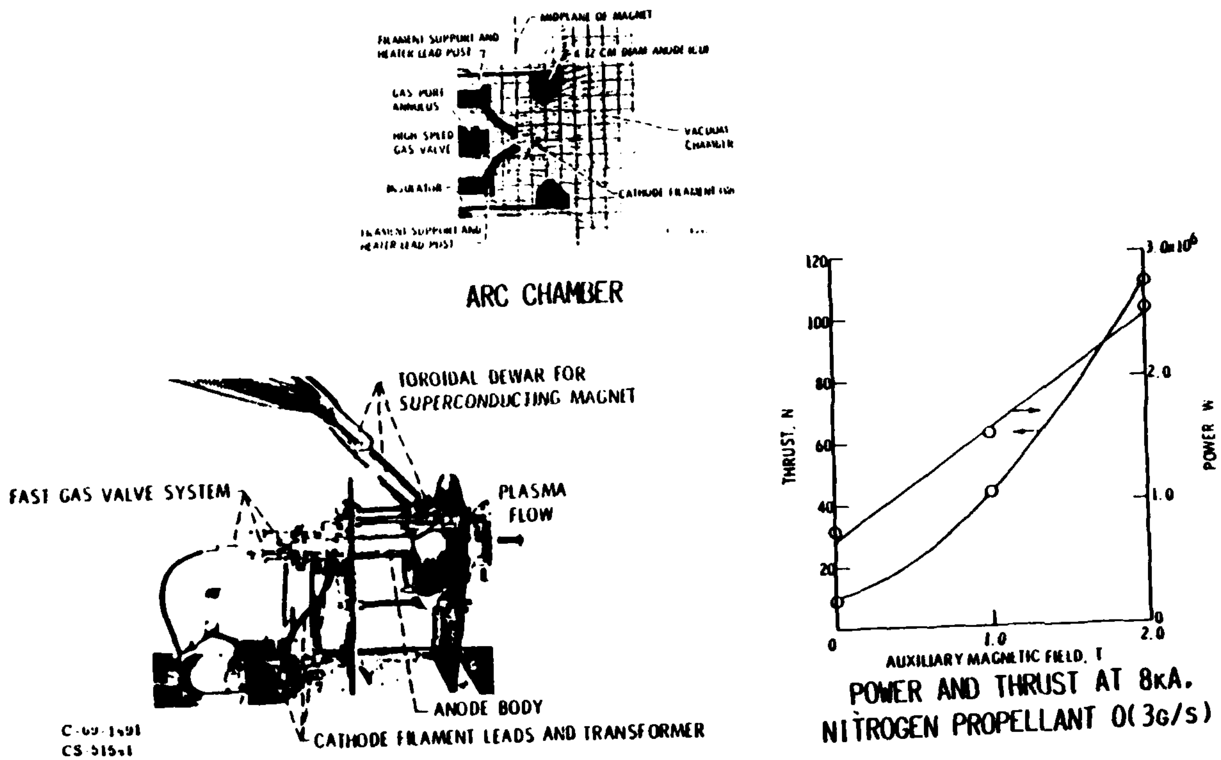


Fig. 2 - Pulsed MW Superconducting Magnet MPD Thruster.
Ref: Michels, C. J. and York, T. M.: AIAA Paper No. 72-500, 1972.

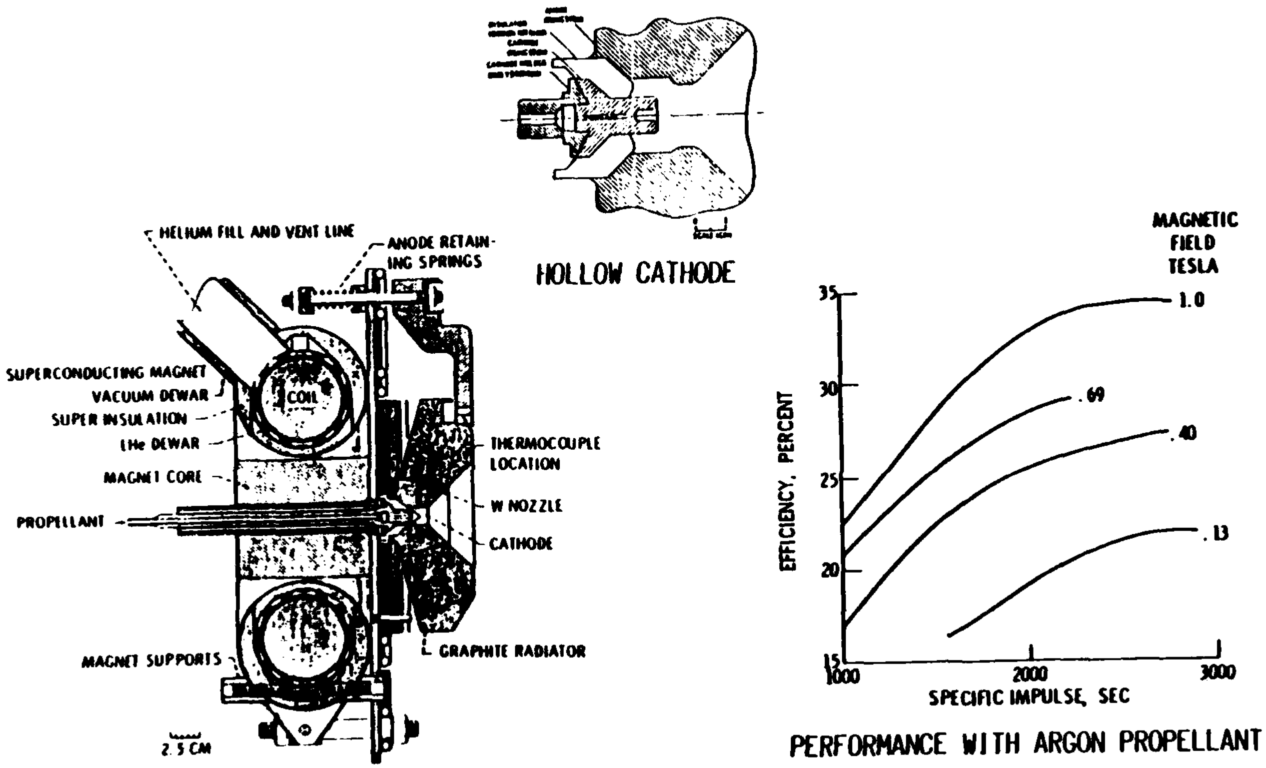


Fig. 3 - 25 kW Radiation Cooled Superconducting Magnetic MPD Thruster.
Ref.: Connolly, D. J.; Bishop, A. R.; and Seikel, G. R.: AIAA Paper No. 71-696, 1971.

lant and a hollow cathode, showed that increasing the magnetic field strength from 0.13 to 1 Tesla at the cathode tip increased the efficiency from 22 to 34 percent. Available superconducting magnet technology would permit even much higher field strengths. It should also be noted that the helium boil-off from the magnet of this thruster was much less than the argon propellant flow.

A life test of this 25kW thruster was conducted using a conical cathode and a water-cooled 0.13 Tesla magnet. It had to be terminated at 553 hours because of rapid erosion of the boron nitride insulator between the thruster's cathode and anode. This resulted from the inability to maintain good control of the current attachment on the conical cathode tip. A hollow cathode was subsequently added to better control the current attachment on the cathode, and this was used for previously discussed high magnetic field strength performance tests. To obtain stable operation with the hollow cathode configuration, however, required that all propellant be introduced through the cathode which in general is not as desirable for performance as anode propellant injection.

Detailed diagnostics of ion and electron temperature were never performed in the exhaust of the high-field strength applied-field thrusters illustrated in Figs. 2 and 3. However, in fusion heating experiments with similar electrode geometries, measurements of ion and electron temperatures were performed. Such experiments were conducted in the high-field strength NASA LeRC Superconducting Magnetic Mirror Apparatus (SUMMA). Results indicated that in such cross-field discharges at very high magnetic field strengths (up to 5 Tesla), the primary heat input is into the ions and the electrons are substantially cooled. In fact, ion temperatures as high as 10 million Kelvin (1 keV) were obtained in hydrogen discharges with less than 3 eV electron temperatures, Ref. 2. In the flow expanding from linear theta-pinch fusion experiments, a similar expansion of hot-ion cold-electron gases has been studied. Results by York, reviewed in Ref. 1, indicated that the expansion is adiabatic and that the ion random energy is converted into directed energy in the magnetic nozzle.

Fig. 4 illustrates a 0.5kW MPD thruster which obtained an efficiency of 37% at a specific impulse of 2200 seconds with xenon propellant. It used an applied magnetic field strength of approximately 0.03 tesla produced by a radiation-cooled edge-wound anodized aluminum coil. The downstream hollow cathode consumed only a small fraction of the propellant flow. However, by controlling the cathode propellant flow it was possible to control the arc impedance of the main discharge. The cathode was located on a magnetic line which passed near the thruster center line. Heating of the upstream backplate assembly limited the power level of this thruster, if the backplate was allowed to become too hot the thruster shifted into a lower voltage, lower efficiency mode.

Fig. 5 illustrates a 0.5kW MPD thruster which was life tested for 1332 hours. Because of the time required to perform the

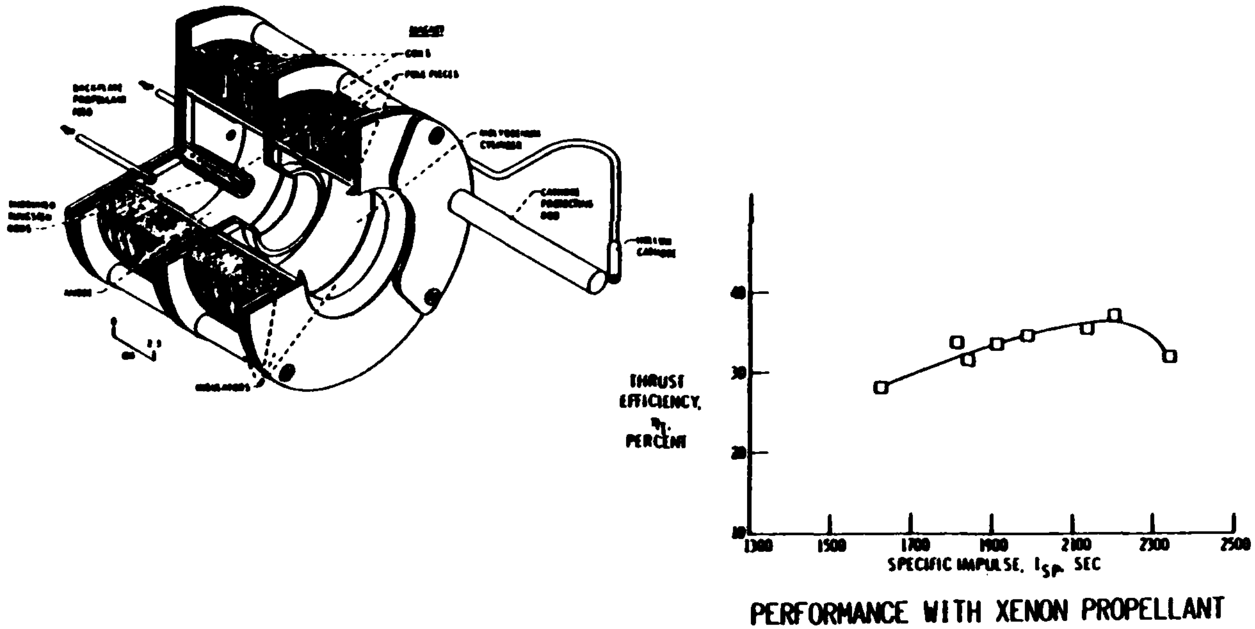
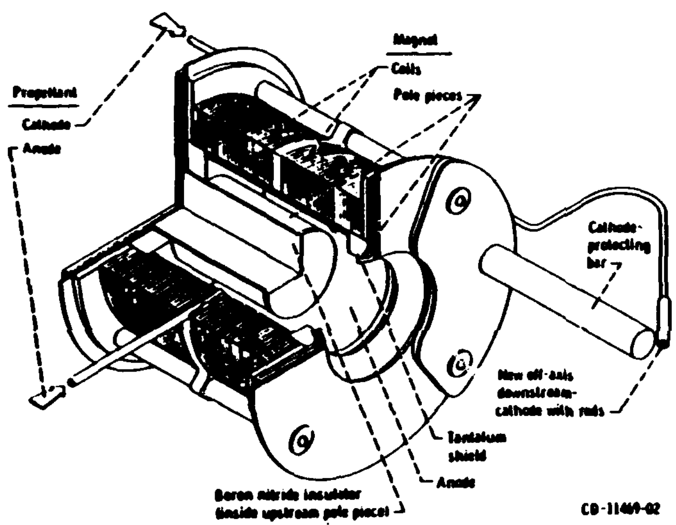
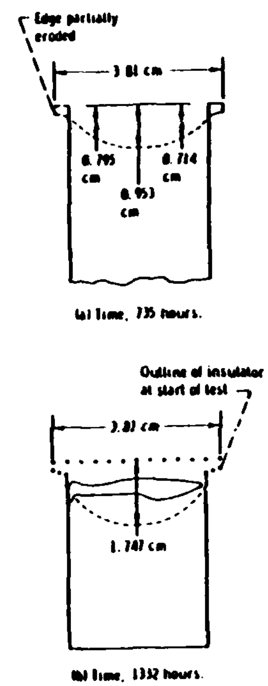


Fig. 4 - High Performance 0.5 kW MPD Thruster.
Ref.: Burkhart, J. A.: AIAA J. or S&R, Vol. 10, No. 1, 1973, pp. 86-88.





BORON NITRIDE INSULATOR

Fig. 5 - 0.5 kW MPD Thruster Life-Tested for 1332 Hours.
Ref.: Burkhart, J. A. and Rose, J. R.: NASA TN D-7616, 1974.

life tests, this thruster was a generation earlier model than that which obtained the highest performance which was discussed and illustrated in Fig. 4. Also shown in Fig. 5 are the cross-section sketches of the thrusters upstream boron nitrite insulator after 735 and 1332 hours of operation. This wear was life limiting and reflected a large inefficiency. Efficiency was improved over 10 points to the previously sighted 37%, by modifications to provide a stronger upstream magnetic mirror field. However, as previously discussed, even the higher performance thruster was power level limited by heating of the backplate.

Fig. 6 illustrates detailed diagnostics test made with a kW MPD thruster with an upstream hollow cathode. These measurements indicated that the thrust is approximately given by the integral of the electron pressure at the thruster exit. Further, the axial voltage gradient was shown to be due to the gradient of the electron pressure. Therefore, the conclusion of these results was that thrust in these low-power low-field MPD thrusters is due to the expansion of a hot-electron cold-ion plasma in the expanding magnetic field or magnetic nozzle.

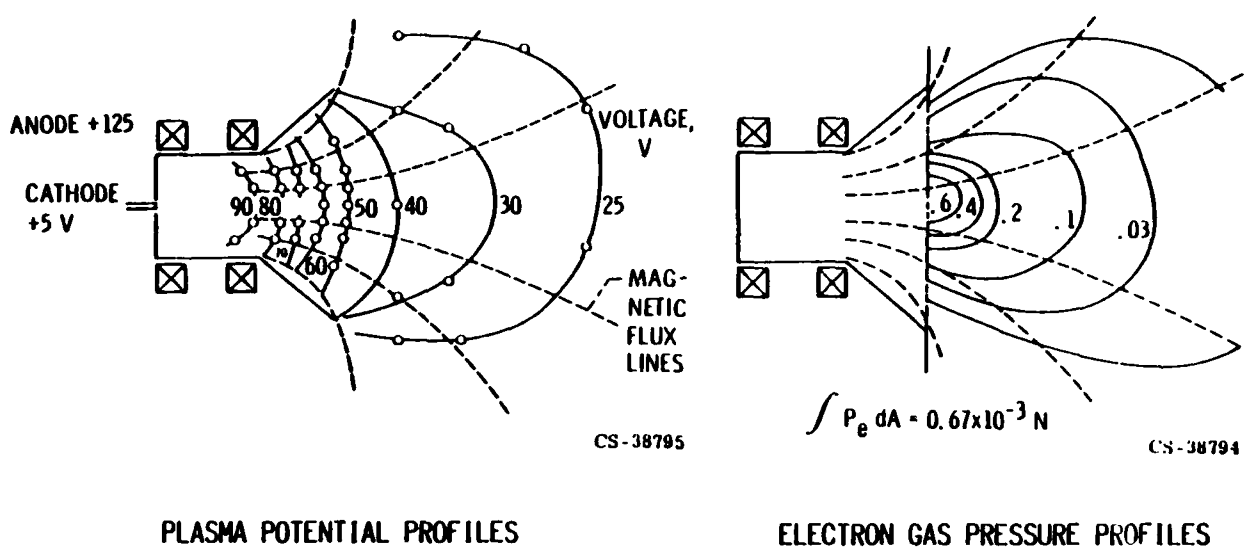


Fig. 6 - Diagnostics of kW MPD Thruster.
Ref.: Bowditch, D. N.: AIAA Paper No. 66-195, 1966.

III. Thruster Performance Analysis

The performance of any DC arc thruster can be evaluated on the basis of a power balance which considers the useful thrust power and all of the various thruster power losses. For a thruster producing a fully ionized exhaust and operating with a specified propellant, mass flow, power level, and voltage, the power balance can be written as indicated in Table 1. The useful power is the thrust power. The major unavoidable power losses are those associated with conducting current to the anode, emitting current from the cathode, ionizing the propellant atoms in the plasma volume, and diffusion and recombinations of plasma on the thruster's surfaces.

In Table 1, only diffusion to a thruster's insulating backplate for the case of cold ions is considered. For thrusters with an applied magnetic field, this is the only thruster component normal to the magnetic field. Therefore, it is the principle recipient of the diffusing plasma. To account for either complete or partial magnetic containment of the plasma, a factor, F, has been included in this backplate loss which can be parametrically varied from 0 to 1. Note, if there is either a population of high-energy electrons on top of the Maxwellian distribution or if the applied magnetic field is shaped to accelerate plasma toward the backplate of the thruster, the backplate loss

Table 1 - DC Discharge Power Balence

Define: Discharge Voltage, V: V Eq. 1a

Discharge Current, A: I Eq. 1b

Power Input ,W: $P = VI$ Eq. 1c

Thrust, N: T Eq. 1d

Mass Flow, kg/s: $\dot{m}$ Eq. 1e

Efficiency: $\eta = T^2/2\dot{m}P$ Eq. 1f

Specific Impulse, s: $I_{sp} = T/g\dot{m}$ Eq. 1g

where g is $9.806 m/s^2$

The Useful Power Is Thrust Power, W: $P_T = T^2/2\dot{m} = g^2\dot{m}I_{sp}^2/2$ Eq. 2

The Power Losses Are: Anode Power, W: $P_A = (2kT_e/e + \phi_A)I$ Eq. 3

Cathode Power, W: $P_C = \phi_C I + P_{RC} = \phi_{Ce} I$ Eq. 4

Ionization Power, W: $P_I = \phi_e \dot{m}e/m_i$ Eq. 5

Backplate Power (Diffusion only, $T_i/T_e \simeq 0$), W:

$P_B = 0.6F\{\phi_e + [2.5+0.5\ln(m_i/2\pi m_e)]kT_e/e\}\dot{m}e/m_i$ Eq. 6

where F is a factor between 0 & 1

P_{RC} is the cathode radiation, W

T_e is electron temperature, K

e is the abs. value of an electron charge, C

k is Boltzmen's constant

$m_{e,i}$ are electron and propellant ion mass, kg

$\phi_{A,C,Ce}$ are the anode, cathode,and effective cathode work functions, V

ϕ_e is effective volume ionization cost, V

Thus $$\eta = \frac{1 - (\phi_A + \phi_{Ce} + 2kT_e/e)/V}{1+\left[\phi_e(1+0.6F)+F\left[1.5+0.3\ln\frac{m_i}{2\pi m_e}\right]\frac{kT_e}{e}\right]\frac{2e}{m_i g^2 I_{sp}^2}}$$ Eq. 7

And also $\eta = \frac{\dot{m}}{2P} g^2 I_{sp}^2$ Eq. 8

For an adiabatic expansion $kT_e/e = 0.2 g^2 I_{sp}^2$ Eq. 9

could be even higher than that due to only diffusion.

For a typical thruster with a molybdenum anode and a hot thoriated tungsten cathode, the sum of the anode work function plus effective cathode work function in Eq. 7 can be well approximated as 10 volts. With this assumption, note that the efficiency given by Eq. 7 would become zero at an electron temperature equal to one half the applied voltage minus 10; all the power would be consumed in anode and cathode losses. Thus, the magnitude of the applied voltage determines an upper bound on electron temperature.

The volume ion production costs in Eq. 7 can be evaluated using the approximate general theory of Dugan and Sovie, Ref. 3. Their theory takes into account the competition between ionizing and exciting collisions of electrons with propellant atoms. Such an approach is strictly valid only for low density, so-called tenuous plasmas. However, a more detailed study of ionizing helium showed that inclusion of collisions with metastable states only slightly affected (increased) the cost of producing ions. Results are illustrated for argon and xenon in Fig. 7. Since the cost of producing ions becomes unbounded as the electron temperature approaches zero, the efficiency given in Eq. 7 becomes zero at zero electron temperature.

With the above assumptions, Eq. 7 can be used to determine how the efficiency of a thruster, operating with a given discharge

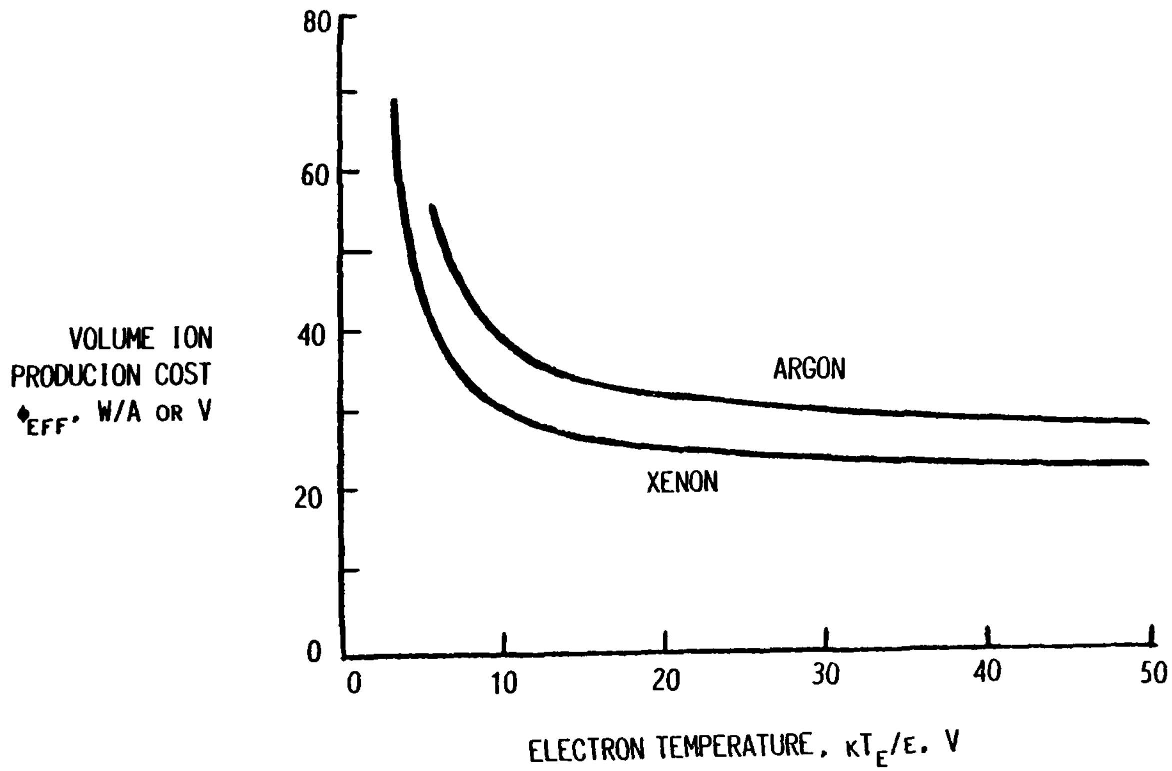


Fig. 7 - Volume Ion Production Cost.

voltage, varies as a function of specific impulse if one can relate electron temperature and the specific impulse. The specific operating point of a thruster operating with a specified mass flow to power ratio can then be determined by the intersection of Eqs. 7 and 8, as illustrated in Fig. 8. Note, generally, the high specific impulse solution is the one of interest. In this example, the expansion of the gases is assumed to be adiabatic and the ion to electron temperature ratio is assumed to be 10. For an adiabatic expansion, the temperatures and specific impulse are related by Eq. 9. It is interesting to also note from Fig. 8 that there is a maximum mass flow to power ratio at which the thruster can operate.

Walker and Seikel, ref. 4, have examined analytically the alternative type of expansion process found in the low power MPD arc thrusters, specifically, the expansion of a fully ionized plasma containing hot electrons and cold ions. They assumed a magnetic nozzle produced by a Helmholtz set of coils, Fig. 9. The analysis is restricted to near the axis of symmetry, and the effects of thermal conduction are included since, as indicated in Fig. 9, these can be very important. The set of equations solved includes the electron and ion continuity and momentum equations, Maxwell's equations, and the electron energy equation. No asymptotic solutions to this nonlinear set of equations for large values of distance were found using classical values of the conductivity for the plasma. As a result, and due to the fact that in experiments major fluctuations are present, an assumption was introduced

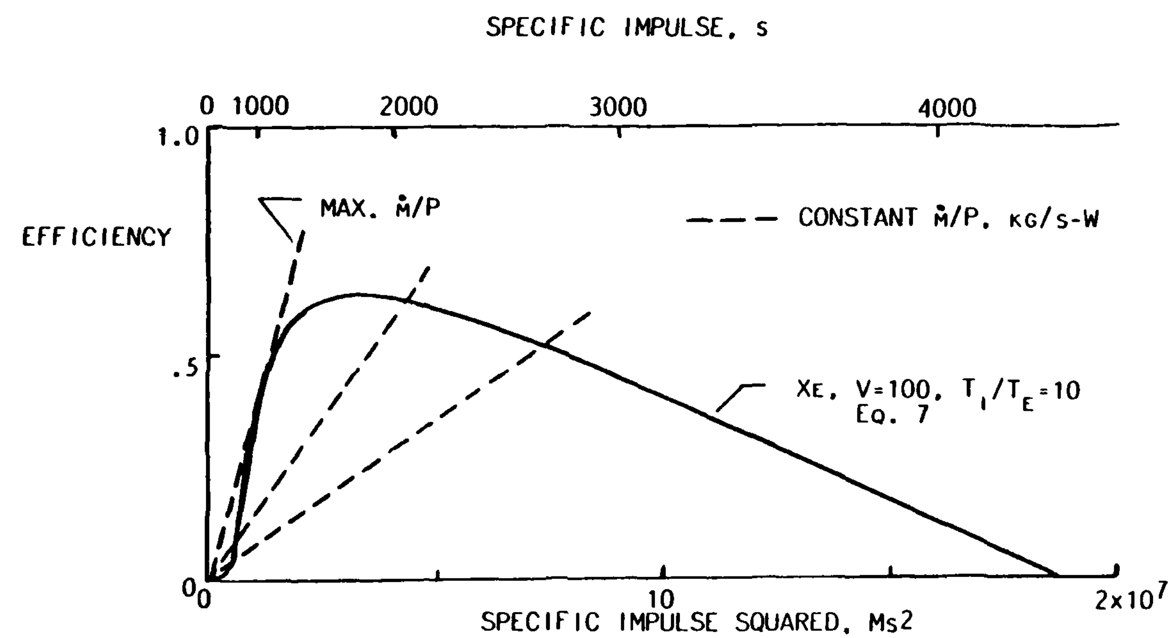


Fig. 8 - Theoretical Electrothermal Applied-Field MPD Thruster Performance. Adiabatic Expansion, No Backplate Losses.

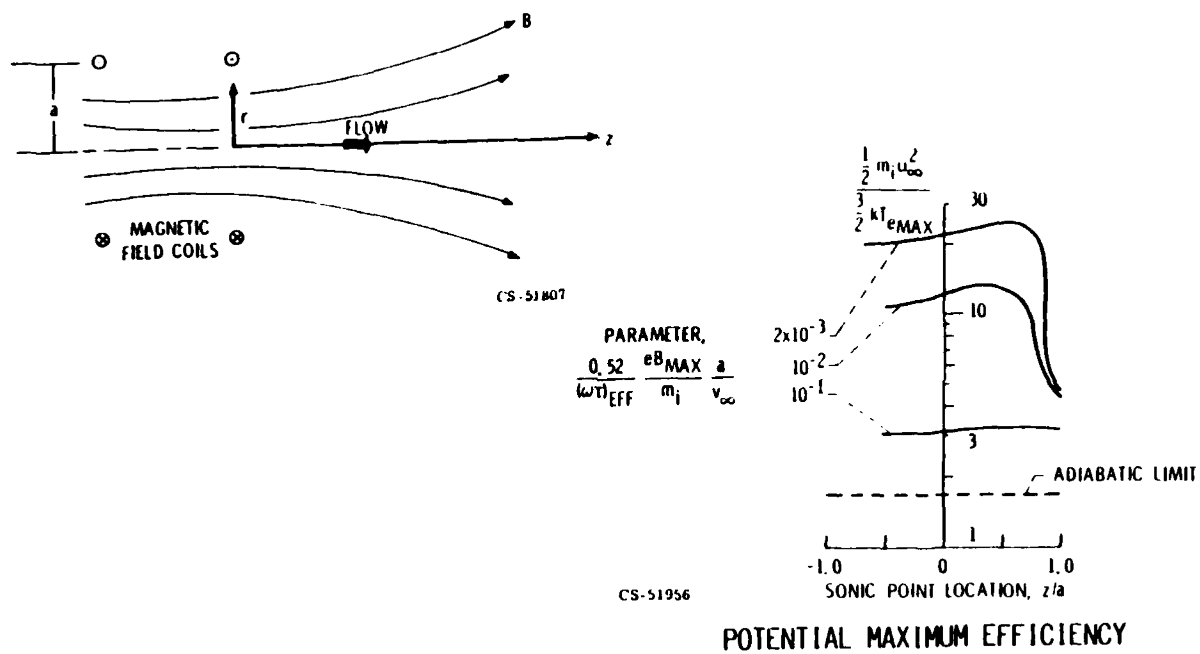


Fig. 9 - Expansion of a Cold-Ion, Hot-Electron Plasma in a Magnetic Nozzle.
Ref.: Walker, E. L., and Seikel, G. R.: *NASA TN D-6154*, 1971.

that the electron collision time could be replaced by an effective time. In particular, the assumption was made that the effective Hall parameter was a constant throughout the flow. Such an assumption assumes a saturation of this parameter which has been experimentally observed in MHD generators and plasma thrusters. Chubb and Seikel (Ref. 5), for example, found that the effective Hall parameter in a Hall current ion thruster saturated at a value of three. This value is also used for the calculations herein.

With this additional assumption, the solutions to the plasma expansion shown in Fig. 9 were obtained. The ordinate is the ratio of final ion energy to initial electron energy, that is, the final ion energy at the end of the expansion divided by the random energy the electrons had before the expansion started. This is plotted against the sonic point location. The sonic point location is relative to the downstream coil in the Helmholtz set. Zero is at the plane of the coil and distance is given in coil radii. The parameter in the analysis is a nondimensional parameter best thought of as a nondimensional magnetic field. As this parameter becomes large, the solutions approach the adiabatic limit.

These solutions illustrate a couple of points. First, the magnitude of the ratio of final ion energy to initial electron energy can be much larger than that of an adiabatic expansion. This illustrates how important thermal conduction can be in such a process. Second, the solutions are quite sensitive to the location of the sonic point in the flow, and therefore, to the divergence of the magnetic nozzle.

The results of Fig. 9 can be used in Eq. 7 to complete the power balance for a low-power MPD arc thruster. Fig. 10 compares the data of the thruster previously discussed and illustrated in Fig. 4 with the results of such an analysis. Three analytical curves are shown. The first is for a thruster with an optimum-shaped magnetic nozzle and no backplate losses. The other two are both for thrusters with much too rapidly expanding magnetic nozzles. One assumes no backplate loss, and the other assumes a maximum diffusion backplate loss.

The pole pieces used in this thruster did produce a rapidly expanding magnetic field. This was done in an attempt to improve containment of the plasma from the backplate. Comparison of the data and analysis would appear to indicate that although some containment is obtained by such a mirror field, the backplate loss is still approximately half of the maximum value for diffusion.

These results indicate that the reason this thruster had higher performance than previous thrusters is solely due to its higher operating voltage. If complete magnetic containment of the plasma is utilized and the shape of the magnetic nozzle is optimized, these results further indicate that thrusters with performance between 50 and 80% should be feasible in the 2500-3500 second specific impulse range.

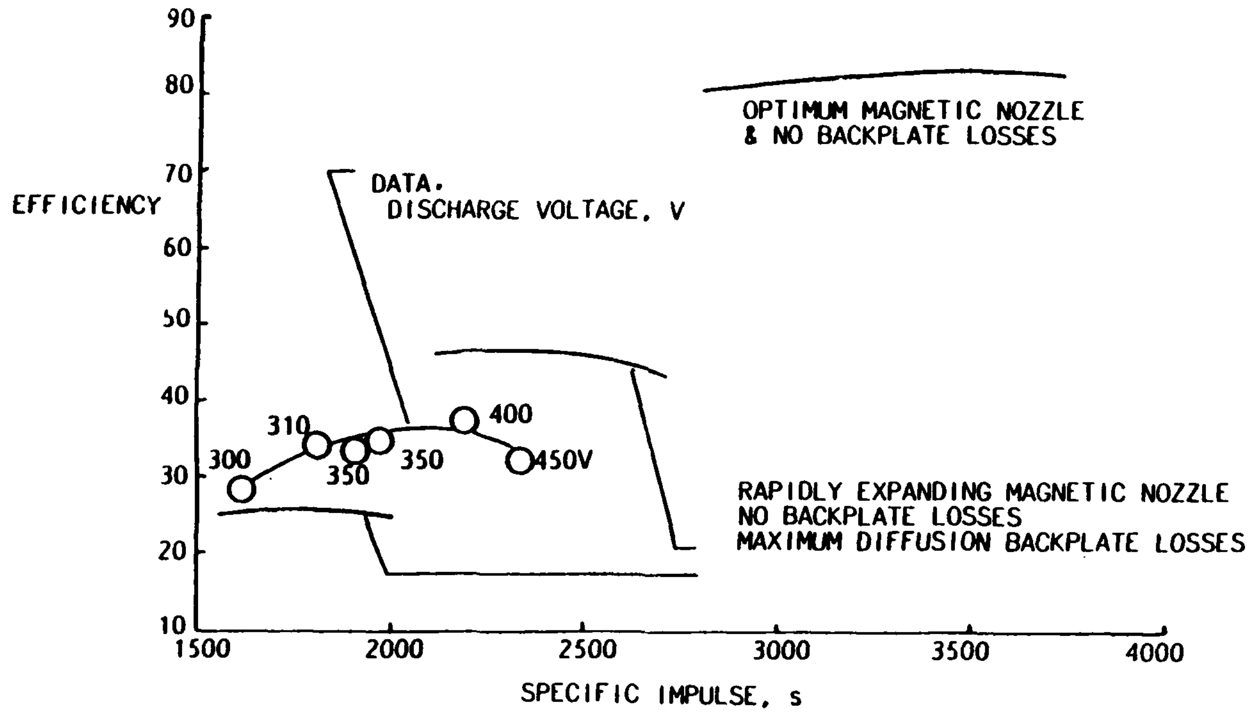


Fig. 10 - Comparison of Experimental and Theoretical Performance of 0.5 kW, 0.03T Applied-Field MPD Thruster.
Fig. 4 Data.

Fig. 11 indicates the performance potential for the high-power, high-magnetic field thrusters in which ion temperature is important and the expansion should be adiabatic. Shown are the anticipated performance for completely magnetically contained xenon thrusters operating at two different voltages and ratios of ion to electron temperature. Also indicated is the expected performance of an equivalent argon thruster. As indicated, these thrusters should also have the potential of approaching 80% efficiency if high ratios of ion to electron temperature are obtained in the discharge.

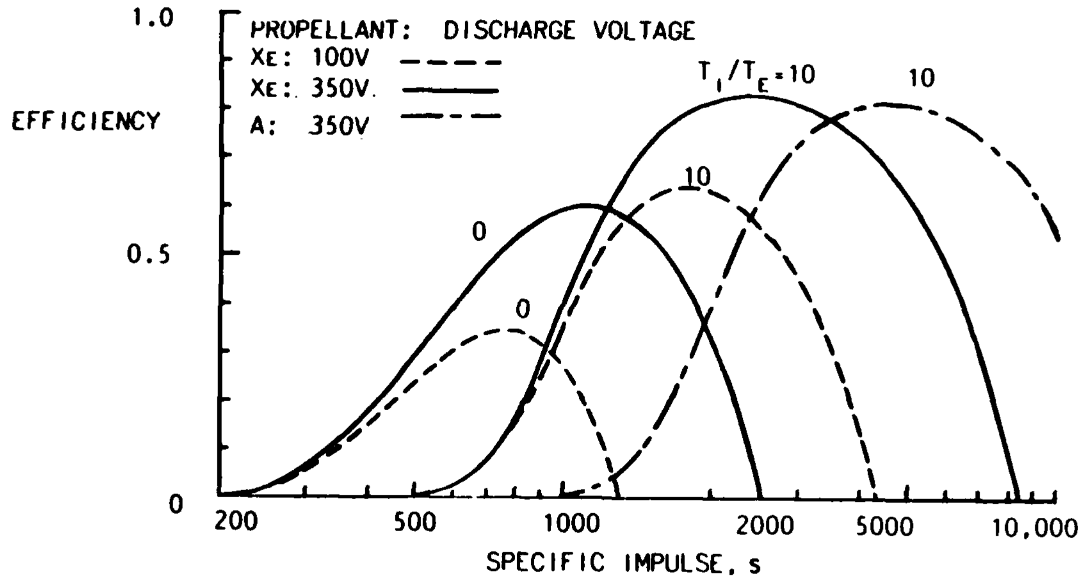
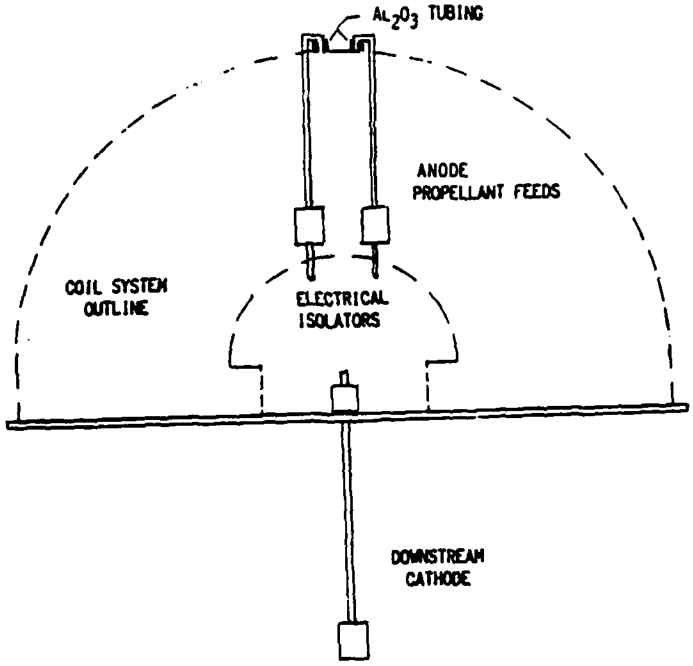


Fig. 11 - Theoretical Performance of High-Power High-Magnetic Field Thrusters.

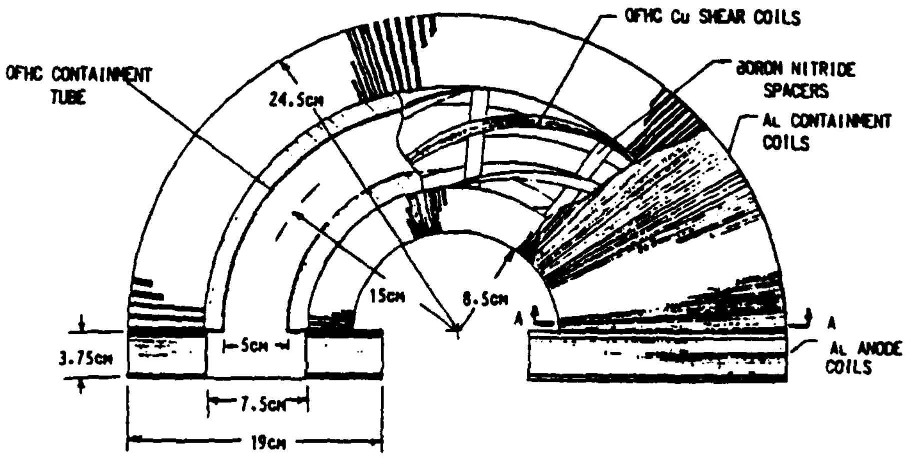
IV. Conceptual Design of kW Steady-State Radiation-Cooled Magnetically Contained MPD Thruster

Conceptual design of this thruster is illustrated in Fig. 12. Fig. 12a, the overall layout, illustrates that propellant is fed through electrical isolators to the downstream hollow cathode and to both anodes through the spaces in the back of the coil system. Fig. 12b illustrates in more detail the coil of the thruster. The coil system is built around a thin wall copper containment tube which has a minor diameter of five centimeters and a major diameter of 30 centimeters in its U shape. The diameter expands to 7.5 cm at the location where the anodes will be inserted. These anodes are where current attachment is expected and where the propellant is introduced into the containment system.

The coil system consists of a number of coils. There are six copper shear windings, which is the minimum number required to obtain shear in the field. That is a twist in the magnetic field lines which causes an azimuthal particle drift around the minor circumference that increases with the magnitude of the particle's minor radius. This is essential for stable containment, Ref. 6. Each shear winding makes one complete turn around the minor circumference of the tube. Currents in adjacent windings are in opposite directions and connected in series.

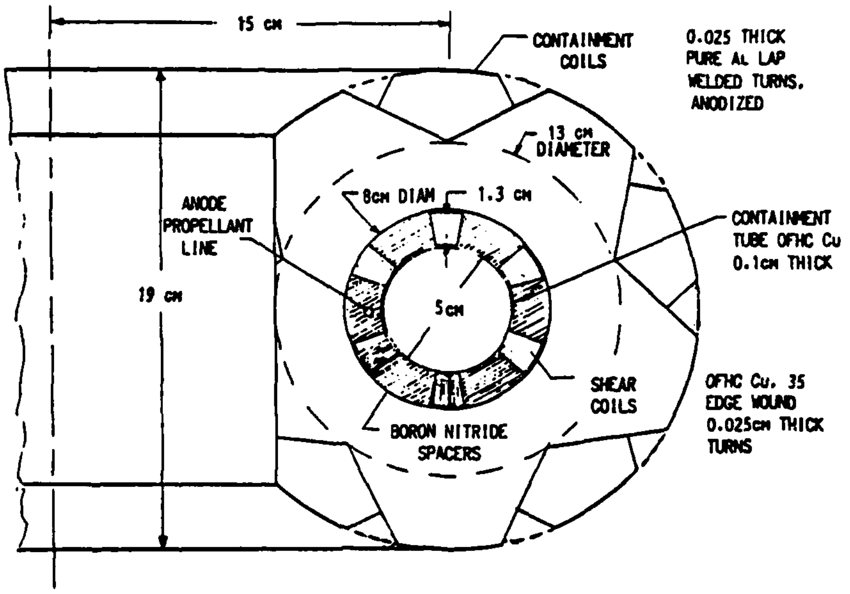


a) Overall Layout

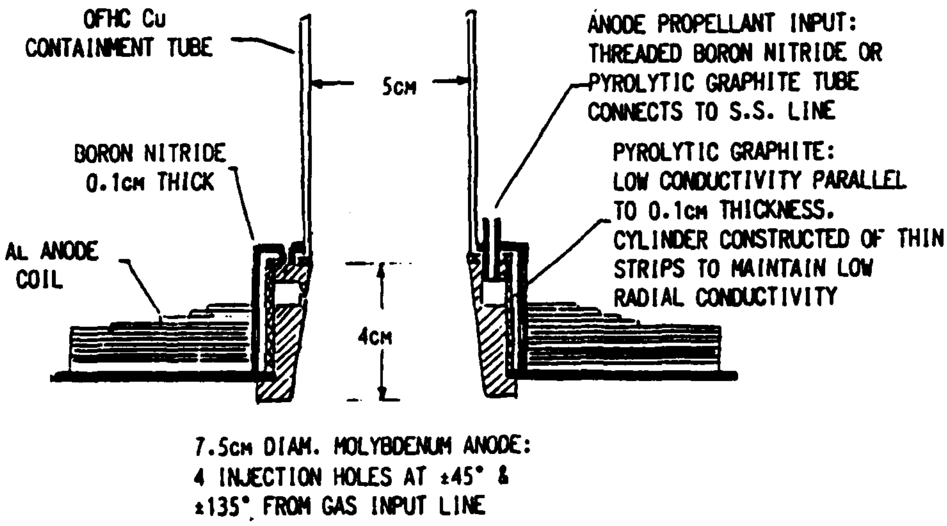


b) Coil System

Fig. 12 - kW Completely Magnetically Contained MPD Thruster.

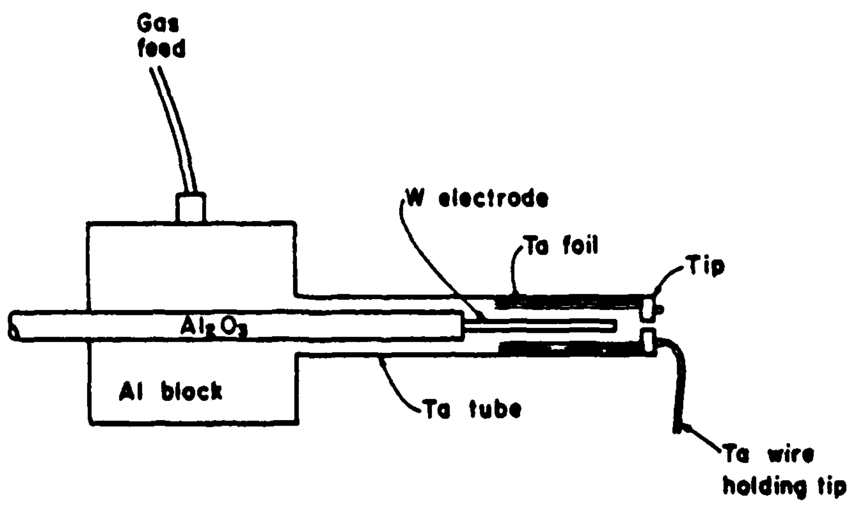


c) Coil System Cross Section



d) Anode Cross Section

Fig. 12 - Continued



e) Hollow Cathode

Fig. 12 - Continued

The shear coils are surrounded by aluminum containment coils. In addition, there are two anode coils positioned over the anode inserts. Power to these coils allows for the variation in the shape of the magnetic nozzle needed to optimize thruster performance.

The nominal design value of the centerline containment field in this thruster is 0.03T. The magnitude of the current in the shear coils was selected so that there is a minimum in the energy of the magnetic field (shear plus containment field) at a major diameter which is 1.5 cm smaller than the maximum major diameter of the containment tube: 20 cm.

At this minor radius, an electron's trajectory would drift more than $1\frac{1}{2}$ revolutions in the direction of minor circumference of the containment tube as it diffuses from one anode thrust head to the other anode thrust head. At smaller minor radii, this azimuthal drift would be proportionally smaller because of the shear of the magnetic field. This twist in the particle's orbit permits current to flow along field lines to short out the electric field which otherwise would form and cause drift of the plasma across the containment field in the direction of its major radii. A minimum of one-half an azimuthal rotation of the particles trajectory is the minimum required to short out these fields.

The coil system is thermally designed so that the copper shear windings radiate their dissipation to the aluminum containment coils, and the containment coils in turn radiate to space both their own and the shear coil dissipation. For the nominal design conditions, the shear coils would operate at a temperature of 755K and the containment coil would be at a temperature of 481K. The total power dissipated in the shear and containment coils would be 645 watts.

Figure 12c shows some additional design details of the containment and shear coils. The containment coil is formed by lap welding thin washers of high-purity aluminum. After welding, the coil would then be anodized to provide the electrical insulation. This is the same construction method on the coils of prior thrusters illustrated in Figs. 4 and 5. In the present design, however, special attention has been paid to minimizing the weight of the containment coil. As illustrated in Fig. 12c, material has been judiciously removed from the outer diameter of the turns of the containment coils to minimize weight and still provide a large effective radiating surface. As illustrated, the anode propellant line flows from the back of the thrusters between the shear coils to the anode inserts.

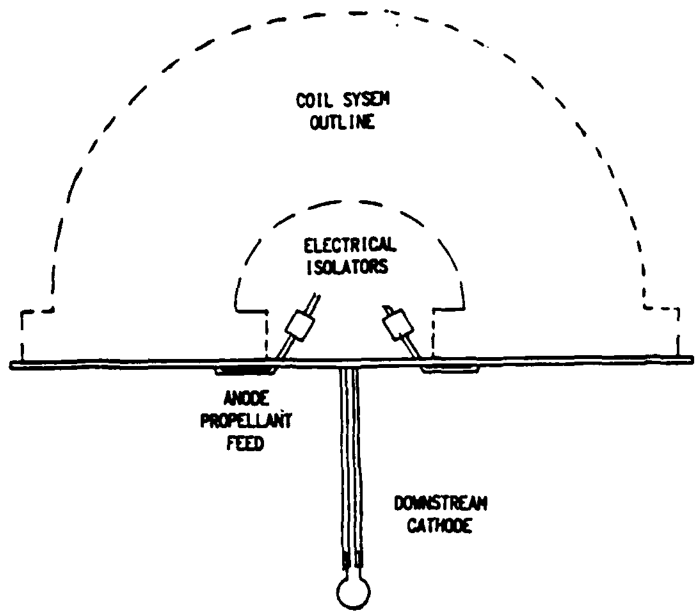
Fig. 12d shows a cross section of the anode inserts. These anodes are constructed from molybdenum and provide for injection of the propellant into the plasma. They are thermally and electrically isolated from the copper containment tube by pyrolytic graphite. Fig. 12e illustrates the type hollow cathode design which would be utilized. This type design was developed and has been successfully used for ion engine neutralizers, Ref. 7. The cathode tip would be located on a magnetic line which passes near the centerlines of both anodes.

V. Conceptual Design of MW Quasi-Steady Magnetically Contained Thruster Experiment

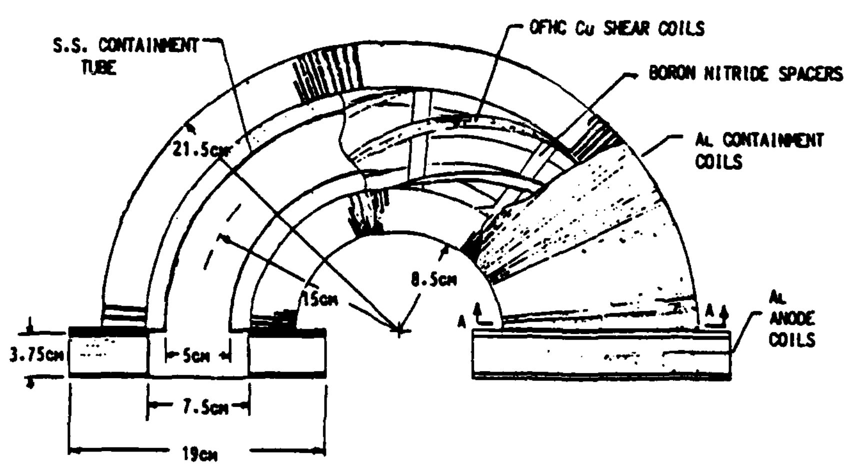
The conceptual design of this thruster is illustrated in Fig. 13. As indicated in Fig. 13a, propellant feeds to the anodes of this thruster will be from downstream via the shortest possible lines from the high-speed gas valve. A hot thoriated tungsten filament will be utilized for the downstream cathode in order to minimize pumping requirements of the test facility.

The thruster's coil system is geometrically and magnetically similar to that designed for the kW thruster, but field strengths have been increased a factor of 33 to a design containment field of 1 Tesla. To operate at high power densities requires high field strengths. Theoretically, the coils system must provide a magnetic field pressure at least four times that of the average of the plasma pressure. Practically, one would not envision operating at a plasma pressure greater than 10% of the magnetic pressure. The magnetic pressure is defined as one half the magnetic flux density squared divided by the permeability of free space.

As indicated in Fig. 13b, the coil system for this thruster is built on a stainless steel containment tube. Because of the pulse nature of the magnetic field, it is desirable to have a higher resistance containment tube so that the time for the field to penetrate the tube is reduced.

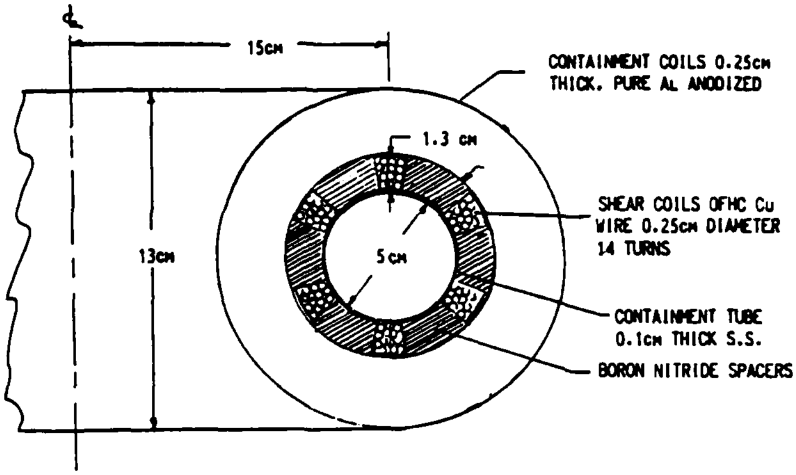


a) Overall Layout

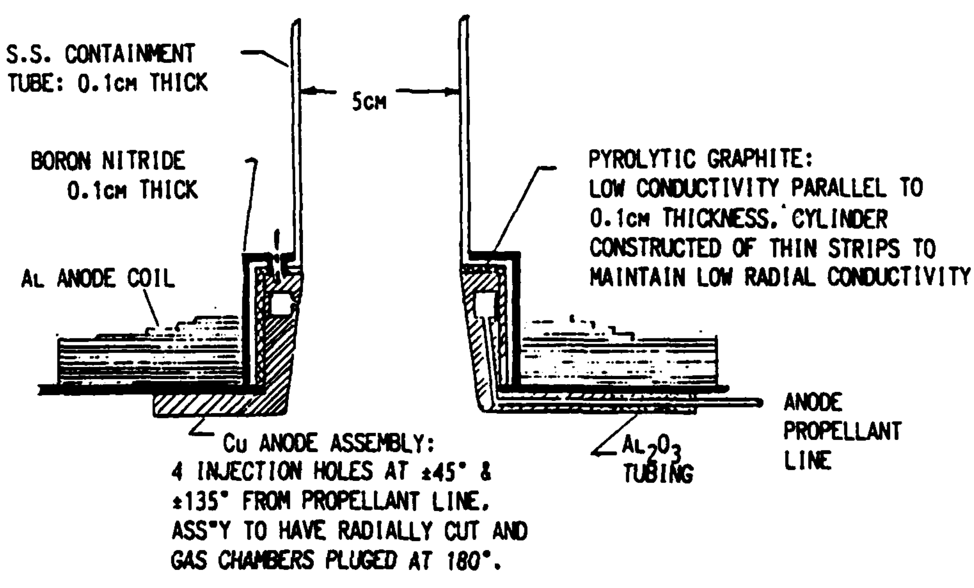


b) Coil System

Fig. 13 - MW Completely Magnetically Contained Thruster Experiment



c) Coil System Cross Section



d) Anode Cross Section

Fig. 13 - Continued

As shown in Figure 13c, the inner diameter of the containment coils is the same as that for the kilowatt thruster, but the outer diameter has been reduced and the thickness of the turns has been substantially increased. The increase in thickness of the containment coils turns and the increase in cross section of the shear coil turns both result from the desire to reduce inductance and limit the required coil operating voltages. Since low-duty cycle operation of the thruster is envisioned, the time average power input to this high-power quasi-steady coil system is less than the steady-state power of the kilowatt thruster's coil system. Therefore, the containment coil outer diameter could be decreased to reduce the difficult of fabrication.

This reduced diameter and increased turn thickness makes it feasible to machine this coil on a lathe. In fact, to insure the feasibility of such an approach, a short coil sample was fabricated by this technique. It did, however, require the use of a novel and unique cutting tool.

Because of the low-duty cycle operation of the thruster, its anodes, as illustrated in Fig. 13d, are constructed of high conductivity copper. The anodes are, as for the kilowatt thruster, thermally and electrically isolated from the containment tube by pyrolitic graphite. This permits independent measurement of currents and heating on the anodes and containment tube.

The anodes have a radial cut to limit the flow of induced currents resulting from field turn on. Otherwise, a significant decay time would be required for the field to penetrate the anodes. The shear and containment coils of the thruster would be powered by SCR switched capacitor banks with diode crowbars. The thruster's discharge would be powered by a 1 millisecond delay line.

VI. References

1. Seikel, G.R.; York, T.M.; and Condit, W.C.: "Applied-Field Magnetoplasmadynamic Thrusters for Orbit-Raising Missions." Orbit-Raising and Maneuvering Propulsion: Research Status and Needs, L.H. Caveny editor. Progress in Astronautics and Aeronautics, Vol. 89, AIAA, N.Y., N.Y., 1984, pp. 260-286.

2. Reinmann, J.J.; Lauver, M.R.; Patch, R.W.; Posta, S.J.; Snyder, A.; and Englert, G.W.: "Hot Ion Plasma Heating Experiments in SUMMA." NASA TM X-71559, 1974.

3. Dugan, J.V. Jr.; and Sovie, R.J.: "Volume Ion Production Costs in Tenuous Plasmas: A General Atom Theory and Detailed Results for Helium, Argon, and Cesium." NASA TN D-4150, 1967.

4. Walker, E.L.; and Seikel, G.R.: "Axisymmetric Expansion of a Plasma in a Magnetic Nozzle Including Thermal Conduction." NASA TN D-6154, 1971.

5. Chubb, D.L.; and Seikel, G.R.: "Basic Studies of a Low Density Hall Current Ion Accelerator." NASA TN D-3250, 1966.

6. Rose, D.J.; and Clark, M. Jr.: Plasma and Controlled Fusion, M.I.T. Press, Cambridge, MA, 1961.

7. Stillwell, R. P.; Robinson, R. S.; Kaufman, H. R.; and Cupp, R. K.: "Experimental Investigation of an Argon Hollow Cathode." AIAA Paper AIAA-82-1880, 1982.

END
12-87
DTIC